AGN PAIRS: CHANCE SUPERPOSITIONS OR BLACK HOLE BINARIES?

M. Dotti

Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany;
mdotti@mpa-garching.mpg.de

M. Ruszkowski

Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI, USA;
e-mail: mateuszr@umich.edu and
The Michigan Center for Theoretical Physics, Ann Arbor, MI, 48109, USA
Draft version December 29, 2009

ABSTRACT

Several active galactic nuclei (AGN) with multiple sets of emission lines separated by over $2000\,\mathrm{km\,s^{-1}}$ have been observed recently. These have been interpreted as being due to massive black hole (MBH) recoil following a black hole merger, MBH binaries, or chance superpositions of AGN in galaxy clusters. Moreover, a number of double-peaked AGN with velocity offsets of $\sim$ a few $10^2\,\mathrm{km\,s^{-1}}$ have also been detected and interpreted as being due to the internal kinematics of the narrow line regions or MBH binary systems. Here we reexamine the superposition model. Using the *Millennium Run* we estimate the total number of detectable AGN pairs as a function of the emission line offset. We show that AGN pairs with high velocity line separations up to $\sim$2000 $\mathrm{km\,s^{-1}}$ are very likely to be chance superpositions of two AGN in clusters of galaxies for reasonable assumptions about the relative fraction of AGN. No superimposed AGN pairs are predicted for velocity offsets in excess of $\sim$ 3000 $\mathrm{km\,s^{-1}}$ as the required AGN fractions would violate observational constraints. The high velocity AGN pair numbers predicted here are competitive with those predicted from the models relying on MBH recoil or MBH binaries. However, the model fails to account for the largest emission line velocity offsets that require the presence of MBH binaries.

Subject headings: black holes – binaries – active galactic nuclei – clusters of galaxies

1. INTRODUCTION

Active galactic nuclei (AGN) with multiple sets of emission lines (EL)[1] redshifted by a large factor ($> 2000\,\mathrm{km\,s^{-1}}$) have been recently discovered (SDSS J092712.65+294344.0, Komossa, Zhou & Lu 2008; SDSS J153636.22+044127.0, Boroson & Lauer 2009; SDSS J105041.35+345631.3, Shields et al. 2009a). The observation of these sources have triggered a huge theoretical effort aimed at understanding their physical nature.

Two models have been proposed as possible explanations for all these AGN. The first one requires the presence of a massive black hole (MBH) binary in the nucleus of each source. The orbital motion of the two components of the binary can result in two sets of EL at two different redshifts if the binary is not orbiting in the plane of the sky (e.g., Begelman, Blandford & Rees 1980). The two sets of ELs would be blue– and red–shifted with respect to the rest frame redshift of the host galaxy. The second model involves the presence of two distinct galaxies that are interacting or simply superimposed within rich galaxy clusters (GCs; hereafter "superposition model"; Heckman et al. 2009; Shields, Bonning & Salviander 2009b; Wrobel & Laor 2009; Decarli et al. 2009a; Shields et al. 2009a). Massive GC have been advocated as a possible explanation for the presence of two superimposed/interacting galaxies with high relative velocity along the line of sight

---

[1] Unless stated otherwise in the text, we collectively refer to AGN broad and narrow emission lines as EL for brevity.

($v_{\mathrm{rel}} \gtrsim 1000\,\mathrm{km\,s^{-1}}$). Apart from its simplicity, the superposition model has two main virtues:

• It can be easily falsified by a non-detection of an overdensity of galaxies in the vicinity of AGN that show multiple sets of ELs (see Decarli, Reynolds & Dotti 2009b).

• The model can account for some of the spectroscopic binary AGN candidates that have been recently identified in the DEEP2 Galaxy Redshift Survey (Comerford et al. 2009) and in the Sloan Digital Sky Survey (Smith et al. 2009; Liu et al. 2009; Wang et al. 2009; Xu & Komossa 2009), that exhibit two sets of ELs at redshifts that imply relative velocities of few hundreds of $\mathrm{km\,s^{-1}}$. Some of those objects can be superpositions in less massive clusters or groups of galaxies, or superpositions in massive GCs between galaxies that move predominantly in the direction tangential to the line of sight.

In this Letter we present an estimate of the total number of superimposed AGN in GCs at $0.1 < z < 0.7$, as a function of their relative velocity, and discuss the implications that this estimate has on the interpretation of AGN with multiple sets of ELs.

2. METHODOLOGY AND RESULTS

Our work is based on the results of the *Millennium Run* (hereafter MR, Springel et al. 2005). We select from the
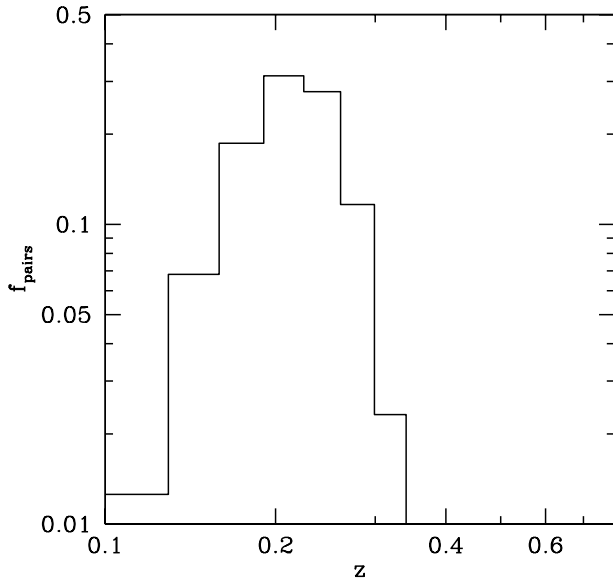
FIG. 1.— Fraction of superimposed galaxy pairs as a function of redshift. The distribution of superimposed AGN is the same by construction.

Virgo-Millennium Database[2] all the GCs in the MR with masses $\gtrsim 10^{13}\,M_\odot$ [3], and redshift between 0.1 and 0.7. The redshift interval has been chosen to coincide with that used by Smith et al. (2009). The upper limit of z has been set to keep [OIII] in a clean part of the spectrum, in order to allow a clear spectroscopic detection of two superimposed AGN. The choice of the minimum redshift limit reduces the number of the low luminosity AGN that would have otherwise been missed at larger redshifts.

We search for the distribution of galaxies in each GC in the online galaxy catalog of De Lucia & Blaizot (2007). We select only those galaxies that are luminous enough to be observed, i.e., those with SDSS u, g, r, i, and z band magnitudes lower then the SDSS magnitude limits. In this sample, we consider only the galaxies that host MBH more massive than $10^5\,M_\odot$.

We select the galaxies that would be observed as superimposed, given the positions of the two galaxies in the MR. Specifically, we consider only superpositions between galaxies in the same GC. This additional criterion ensures that our results provide a lower limit to the number of pairs, because we neglect (1) the superpositions between field galaxies, (2) between a field galaxy and a galaxy in a GC, and (3) between two galaxies in two different GCs. Two galaxies are considered superimposed if their angular separation is lower than 3 arcsec, i.e., the angular resolution of the SDSS spectra.

We then integrate over redshift, i.e., we sum the pairs detected in all GCs in different redshift snapshots of the MR renormalizing the number of pairs in each redshift interval by the ratio between the physical volume of the Universe and the comoving volume simulated in the MR.

We renormalize the distribution of superimposed galaxies to compute the distribution of superimposed AGN. Based on the complete fraction of low redshift ($z < 0.1$) SDSS galaxies, Kauffmann et al. (2004) estimated that the fraction of AGN with [OIII] line luminosities larger than $10^7\,L_\odot$ ($L_{[OIII]} > 10^7\,L_\odot$) is $f_{AGN} \sim 6\%$ in high galaxy density regions. Majority of galaxies in the highest density regions (largest neighbor number) considered by Kauffmann et al. (2004) reside in the dark matter halos of masses exceeding $10^{13}\,M_\odot$, i.e., in galaxy groups and clusters (see Figure 16, right panel in Kauffmann et al. 2004). The AGN fraction in galaxies less massive then $\sim 10^{10}\,M_\odot$ is lower then the assumed f_{AGN}. However, the fraction of pairs with at least one component less massive then $10^{10}\,M_\odot$ is typically around $\sim 0.5\%$ and, thus, such low mass galaxies do not affect our conclusions. We limit our study to the case where both galaxies in a given pair are active. As a consequence, only 0.06^2 of our pairs are considered AGN pairs (i.e., 0.36%). We note that, for a given f_{AGN}, the expected number of systems with multiple ELs obtained under this assumption is a lower limit, as under particular conditions two sets of ELs can be produced by an AGN/inactive galaxy pair (Heckman et al. 2009). That is, a second set of narrow ELs can be produced by an inactive galaxy if it is close enough to an AGN, so that the gas is photoionized by the AGN continuum. Our requirement that both the galaxies are active assures that they can be observed as multiple line emitters, regardless of their separation or their luminosity.

Because our study concerns AGN at redshifts higher then those in the Kauffmann et al. (2004) sample, it could in principle select a higher luminosity subsample of them. The fraction of AGN is a decreasing function of the [OIII] luminosity (see right panel of Figure 9 in Kauffmann et al. 2004), so at larger redshift we expect lower f_{AGN}. Because our predicted distribution of AGN pairs peaks at $z \approx 0.2$, the luminosity distances of our systems are $\gtrsim 4$ times those of the AGN in Kauffmann sample. As a consequence we could be selecting AGN with $L_{[OIII]} > 10^8\,L_\odot$, that would correspond to f_{AGN} smaller by $\sim$ one order of magnitude. Therefore, we also consider ten times lower f_{AGN} in order to obtain a conservative lower number of superimposed AGN. However, a significant fraction of AGN with $L_{[OIII]} > 10^7\,L_\odot$ AGN may still be detectable at $z \sim 0.2$. We also that the number of AGN in this sub-sample is conservative also because, if AGN itself is luminous enough, it can be observed even if the luminosity of the galaxy is too faint to be detected. Finally, for low z the intrinsic AGN fraction increases with redshift.

Figure 1 shows the fraction of superimposed galaxies (f_{pairs}) as a function of redshift. We note that this distribution is by construction equal to the distribution of superimposed AGN, given that we assumed the AGN-to-galaxy ratio to be independent of redshift. We note that this assumption does not strongly affect our results because the distribution of galaxy pairs is strongly peaked at $z \approx 0.2$ and does not extend to $z \gtrsim 0.4$. The distribution of galaxy pairs has a clear peak. This distribution can be used to used to constrain the models. For example, the AGN pairs at $z \gtrsim 0.5$ are unlikely to be consistent with superposition model given the SDSS limits.
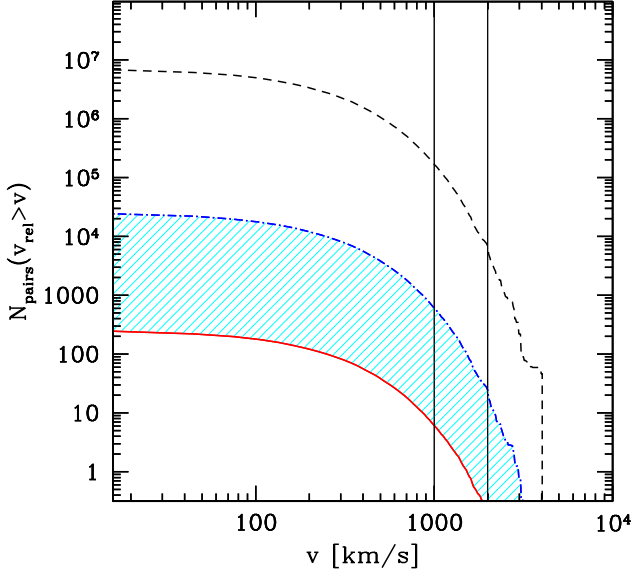
FIG. 2.— Cumulative number of superimposed galaxy pairs (black dashed line) and AGN pairs (blue dot–dashed and red solid lines) with relative velocity along the line of sight larger than v. Blue (red) line has been obtained using $f_{\rm AGN} = 6\% \, (0.6\%)$. The thin vertical lines highlight the number of pairs with relative velocity larger than 1000 and 2000 km s^{-1}, respectively.

The peak in the distribution occurs for two reasons:

• The small number of pairs at low z is due to the fact that the volume of the universe enclosed within $z \lesssim 0.1$ is relatively small and so is the number of GCs in that region. Furthermore, a galaxy pair at a given physical separation may appear to be separated by 3 arcsec and count as superimposed pair when it is at higher redshift but may be resolved when it is at low z thereby lowering the expected superimposed pair fraction at small redshifts.

• At higher z, the number of massive clusters decreases with redshift in accordance with hierarchical model of structure formation. The decline in the number of pairs at high z is also caused by the SDSS magnitude limits.

Figure 2 shows the main results of our study. The black dashed line refers to the superimposed galaxy pairs. The blue dot–dashed line refers to the AGN pairs, assuming $f_{\rm AGN} = 6\%$. We find that over $\sim 10^4$ superimposed AGN are expected from our simple model. The majority of these would not be recognized as pairs because their relative velocity is too small. The spectra of superimposed pairs with $v_{\rm rel} \sim 100$ km s^{-1} would not appear peculiar. In fact, the coexistence of two different sets of ELs with correspondingly small redshift difference can be due to the dynamics within a single galaxy (e.g., due to a disk-like structure in the narrow line region or due to the presence of winds, see, e.g., Crenshaw et al. 2009 and references therein). If two superimposed AGN are Type I, and have such a small relative velocity, it would be extremely difficult (or impossible) to deconvolve the two broad line sets from the spectrum. Nevertheless, a significant number of superimposed AGN with high relative velocities is present. We predict $N_{\rm pair} \gtrsim 500$ AGN pairs have $v_{\rm rel} > 1000$ km s^{-1}, and $N_{\rm pair} \approx 18$ pairs with

$v_{\rm rel} > 2000$ km s^{-1}.

These results seem to be in contrast with the paucity of observed AGN with multiple sets of ELs (Comeford et al. 2009; Smith et al. 2009, Liu et al. 2009; Wang et al. 2009; Xu et al. 2009). In these studies, the authors find few hundred systems with a difference in redshift corresponding to $v_{\rm rel} \gtrsim 100$ km s^{-1}, while we find ≈ 4000 pairs with $v_{\rm rel} \gtrsim 500$ km s^{-1}. However, our results can match these observations if we conservatively assume $f_{\rm AGN} = 0.6\%$ (red solid line in Figure 2). In this case, the total number of AGN superpositions is ~ 200. Therefore, even for this conservative assumption for $f_{\rm AGN}$, a considerable fraction of the binary AGN candidates with low relative velocities can be explained as AGN superpositions in GCs. We emphasize that AGN fraction higher then 0.6% can be consistent with the data as the surveys performed to date do not cover the whole sky.

As a consequence of the above change in the normalization in $f_{\rm AGN}$, the number of superpositions with $v_{\rm rel} > 1000$ km s^{-1} is 5, while no AGN pairs are found for $v_{\rm rel} > 2000$ km s^{-1}. Therefore, in this conservative limit, none of the high velocity superposition candidates (SDSS J092712.65+294344.0, SDSS J153636.22+044127.0, and SDSS J105041.35+345631.3) would be consistent with a superposition of two AGN in galaxy clusters. However, the superposition model could still account for the faint AGN-quasar pair in SDSS J153636.22+044127.0 (see below).

We expect the real distribution of superimposed AGN in clusters to lie in the region between the blue dot–dashed and the red solid lines in Figure 2. We note that for the case where either every galaxy in GCs hosts an AGN or, equivalently, we do not require the two galaxies host AGN in order to be spectroscopically detected as a pair ($f_{\rm AGN} = 1$), we do not expect any pair with $v_{\rm rel} > 4000$ km s^{-1}.

3. DISCUSSION

We analyzed the dynamical properties of galaxies in clusters and groups of galaxies in the De Lucia & Blaizot galaxy catalog based on the *Millennium Run*. We computed the total number of superimposed AGN pairs in the whole sky as a function of galaxy relative velocity along the line of sight and under the assumption that a fixed fraction of galaxies are in the active phase and taking into account the SDSS magnitude and angular resolution limits. We find that, for $0.6\% \lesssim f_{\rm AGN} \lesssim 6\%$, the expected cumulative number of AGN pairs with small velocity separations of $v_{\rm rel}$ ($\gtrsim 100$ km s^{-1}) is always $\gtrsim 200$ within $z \approx 0.3$. In the most optimistic case, this number increases to $\sim 2 \times 10^4$. This can explain a substantial fraction (if not all) of the AGN with multiple sets of ELs extracted from the SDSS and DEEP2 surveys (e.g., Liu et al. 2009). However, some of those objects can be explained in terms of internal dynamics of gas in the NLR (e.g., Crenshaw et al. 2009).

The AGN pairs with velocity separations $v_{\rm rel} \gtrsim 500$ km s^{-1} are more difficult to explain in terms of internal dynamics of single galaxies then those characterized by smaller velocity differences. For $v_{\rm rel} \gtrsim 500$ km s^{-1}, we find between ~ 40 and a few $\times 10^3$ AGN pairs depending on the assumed AGN fraction which can account for a

sizable fraction of the observed AGN pairs at this velocity separation.

For $v_{\rm rel} \gtrsim 1000\,{\rm km\,s^{-1}}$, we find more than 5 AGN pairs. This number can increase up to 500 if we optimistically assume that a large fraction of galaxies in GCs host AGN ($f_{\rm AGN} = 6\%$). AGN showing multiple sets of ELs corresponding to such extreme velocities cannot be explained in terms of internal dynamics of a single galaxy but can be easily accounted for in the superposition model. We also note that similar (or even larger) relative velocities are predicted by two other models: (1) the binary model, and (2) the recoiling MBH model where a set of ELs is comoving with a recoiling MBH – a remnant of a MBH binary coalescence (Komossa et al. 2008). However, even these models predict very few events ($\lesssim 20$ for the binary model, Volonteri, Miller, Dotti 2009; $\lesssim 1$ for the recoil model, Dotti et al. 2009; Shields et al. 2009). Therefore, the superposition model appears at least equally competitive in this case.

However, three AGN with multiple sets of emission lines shifted by even larger amount (more than $2000\,{\rm km\,s^{-1}}$) have been recently detected. It is interesting to compare our results with such extreme sources.

SDSS J092712.65+294344.0 has two sets of ELs corresponding to $v \approx 2650\,{\rm km\,s^{-1}}$. From the theoretical point of view, it could in principle be due to AGN superposition in a very massive GC if we assume $f_{\rm AGN} \sim 6\%$. However, the redshift of the cluster ($z \approx 0.7$) is inconsistent with the redshift distribution of superimposed AGN pairs that we obtained in this analysis (see Figure 1). Moreover, Decarli et al. (2009b) compared multiple band images of the field containing SDSS J092712.65+294344.0 and proved that the presence of such a massive GC is in disagreement with the paucity of galaxies in that field.

SDSS J105041.35+345631.3 and SDSS J153636.22+044127.0 have multiple sets of ELs with $v_{\rm rel} = 3500\,{\rm km\,s^{-1}}$. Such high velocities are inconsistent

with any reasonable value of $f_{\rm AGN}$. Because these quasars show two distinct sets of broad lines, a model with a recoiling MBH does not apply. For these objects other explanations, implying the presence of MBH binaries or a non axisymmetric broad line region (such as double peaked quasars see, e.g., Eracleous & Halpern 2003; Gezari, Halpern & Eracleous 2007), are required.

SDSS J153636.22+044127.0 has been the subject of follow–up observations. Decarli et al. (2009a) found a significant overdensity of galaxies that suggested the presence of a moderately rich cluster. Furthermore, they discovered a second galaxy, within ≈ 1 arcsec from the quasar host. The companion hosts an optically faint AGN, clearly detected in radio by Wrobel et al. (2009). No direct estimate of the redshift of the companion has been reported to date. This quasar-AGN pair can be easily understood in terms of our model, and could be an example of a case where one of the AGN is not bright enough to possess clearly detectable emission lines.

Our investigation shows that an AGN pair with two sets of ELs shifted by $500 \lesssim v_{\rm rel} \lesssim 2000\,{\rm km\,s^{-1}}$ is likely to be a chance superposition of two AGN provided that the pair is located in dense environment. On the other hand, the superposition model does not predict sources with $v_{\rm rel} \gtrsim 3000\,{\rm km\,s^{-1}}$, even in the best case scenario. Even assuming that every galaxy is an AGN, no pairs with $v > 4000\,{\rm km\,s^{-1}}$ are expected to be observed. The maximum velocity for the superposition model is very similar to the maximum recoil velocity predicted by fully relativistic simulations of MBH coalescence ($v_{\rm rel} \approx 4000\,{\rm km\,s^{-1}}$, Campanelli et al. 2007). AGN with larger shifts and multiple sets of narrow ELs cannot be explained as standard double peaked emitters. Such AGN are likely to be close MBH binaries.

REFERENCES

Begelman, M.C., Blandford, R.D., & Rees, M.J. 1980, Nature, 287, 307

Bogdanovic, T., Eracleous, M., & Sigurdsson, S. 2009, ApJ, 697, 288

Boroson, T.A., & Lauer, T.R. 2009, Nature, 458, 53

Campanelli, M., Lousto, C.O., Zlochower, Y., & Merritt, D., 2007, ApJ, 659, L5

Comerford, J.M., et al. 2009, ApJ, 698, 956

Crenshaw, D.M., Schmitt, H.R., Kraemer, S.B., Mushotzky, R.F., & Dunn, J.P. 2009, accepted for publication in ApJ (arXiv:0911.0675)

Decarli, R., Dotti, M., Falomo, R., Treves, A., Colpi, M., Kotilainen, J.K., Montuori, C., & Uslenghi, M. 2009a, ApJ, 703, L76

Decarli, R., Reynolds, M.T., & Dotti, M. 2009b, MNRAS, 397, 458

De Lucia, G., & Blaizot, J., 2007, MNRAS, 375, 2

Dotti, M., Montuori, C., Decarli, R.,Volonteri, M., Colpi, M., & Haardt, F. 2009, MNRAS, 398, L73

Eracleous, M., & Halpern, J.P. 2003, ApJ, 599, 886

Gezari, S., Halpern, J.P., & Eracleous, M. 2007, ApJ, 169, 167

Heckman, T.M., Krolik, J.H., Moran, S.M., Schnittman, J., & Gezari, S. 2009, ApJ, 695, 363

Kauffmann, G., White, S.D.M., Heckman, T.M., Menard, B., Brinchmann, J., Charlot, S., Tremonti, C., & Brinkmann, J., 2004, MNRAS, 353, 713

Komossa, S., Zhou, H., Lu, H., 2008, ApJ, 678, L81

Lauer, T.R., & Boroson, T.A. 2009, submitted to ApJ Letters (arXiv:0906.0020)

Liu, X., Shen, Y., Strauss, M.A., & Greene, J.E. 2009, accepted for publication in ApJ (arXiv:0908.2426)

Shields, G.A., et al. 2009a, ApJ, 707, 936

Shields, G.A., Bonning, E.W., & Salviander, S. 2009b, ApJ, 696, 1367

Smith, K.L., Shields, G.A., Bonning, E.W., McMullen, C.C., & Salviander, S. 2009, submitted to ApJ (arXiv:0908.1998)

Springel, V., et al. 2005, Nature, 435, 629

Volonteri, M., Miller, J.M., & Dotti, M., 2009, ApJ, 703, L86

Xu, D., & Komossa, S., 2009, ApJ, 705, L20

Wang, J., Chen, Y., Hu, C., Mao, W., Zhang, S., & Bian, W., 2009, ApJ, 705, L76

Wrobel, J.M., & Laor, A. 2009, ApJ, 699, L22